10/527935
DT12 Rec'd PCT/PTO 16 MAR 2005

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[10191/4148]

INTERFEROMETRIC MEASURING DEVICE

The present invention relates to an interferometric measuring device for recording the shape, the roughness or the distance to the surface of a measured object, using a modulation interferometer to which short-coherent radiation is supplied by a radiation source and which has a first beam splitter for splitting the radiation supplied into a first beam component guided via a first arm, and into a second beam component guided via a second arm, of which the one is shifted with respect to the other with the aid of a modulating device in its light phase or light frequency, and passes through a delay line, and which subsequently are united at an additional beam splitter of the modulation interferometer, and having a measuring probe, that is spatially separated from the modulation interferometer and is coupled or able to be coupled to the latter via an optical fiber device, in which the combined beam components are split up into a measuring beam that is guided to the surface by a probe-optical fiber unit having a slantwise exit surface at the object end, and a reference beam, and whereupon the measuring beam reflected at the surface and the reference beam reflected at a reference plane are superimposed, and having a receiver device and an evaluating unit for converting the radiation supplied to it into electrical signals and for evaluating the signals on the basis of a phase difference.

Background Information

Such an interferometric measuring device is described in DE 100 57 539 A1. In this known measuring device, the interferometric measuring device is subdivided, on the one

hand, into a modulation interferometer and, on the other hand, into a measuring probe having an additional interferometer unit. In the measuring probe there is provided a probe-optical fiber unit having an exit surface at the object end which, for instance, may be beveled. No more precise statements are made with respect to this. By the way, such an interferometric measuring device works in a manner described in greater detail in connection with DE 198 19 762 A1.

An additional interferometric measuring device is given in DE 198 19 762 A1. In this known measuring device, one part, the so-called modulation interferometer, is spatially separated from the actual measuring probe, and is optically connected to it via a light-conducting fiber system, so that the measuring probe per se may be designed as a relatively simply constructed, easily manipulable unit. A broad-band, short-coherent radiation is supplied to the modulation interferometer, which is split into two beam components at the input of the modulation interferometer with the aid of a beam splitter, of which the one is shifted in its light phase or light frequency with respect to the other, using a modulation device, such as an acousto-opctic modulator. In the modulation interferometer, one of the two beam components runs through a delay element which generates an optical path difference of the two beam components which is greater than the coherence length of the short-coherent radiation. In the measuring probe, in a measuring arm, with respect to a reference arm, an additional optical path difference is generated in such a way that the path difference effected by the delay element is compensated for, and, consequently, an interference is created of the reference radiation coming from the reference plane of the reference arm and the radiation coming back from the object surface in the measuring arm, which is subsequently analyzed so as to ascertain the desired surface property

(shape, roughness, clearance distance) via a phase evaluation. In the measuring probe, the measuring arm and the reference arm are situated in one exemplary embodiment in one common light path (common path), a partially transmitting optical element being provided for forming the measuring arm and the reference arm.

A similar interferometric measuring device having such a modulation interferometer and a measuring probe connected to it via a light-conducting fiber system is also described in DE 198 08 273 A1, in a beam splitting and radiation detecting unit, using a receiving equipment, a splitting of the radiation brought to interference into radiation components of different wavelength taking place, so as to form therefrom a synthetic wavelength and to increase the measuring range (range of unambiguity).

In the interferometric measuring devices named above, which are based on heterodyne interferometry, but which utilize the properties of a broad-band, short-coherent radiation, the modulation interferometer, designed as a Mach-Zehnder interferometer, has a system of classical optical components, such as collimation optics lying upstream of the input end of the beam splitter, the beam splitter and reflecting mirror at the input end and the output end. In this context, the beam components experience several reflections at the beam splitter surfaces and at the mirrors, before they are coupled in to the optical light-conducting fiber system. The optical components have to be positioned with great accuracy, since the effect of every angle error is doubled by the reflection. In this context, it is difficult to ensure the durability of a calibration. In connection with fitting in a glass plate to compensate for optical asymmetries, too, additional difficulties come about during the calibration. A costly construction is connected with these difficulties, an exact

adjustment to the properties of the measuring probe being also required.

The present invention is based on the object of making available an interferometric measuring device of the type mentioned at the outset, which permits achieving as accurate as possible a measurement, using a simplified construction.

Summary of the Invention

This object is attained by the features set forth in Claim 1. According to this, it is provided that the angle of inclination of the exit surface with respect to the normal of the optical probe axis is at least 46^0.

Using this design of the exit surface, one achieves an optimal coupling behavior in the case of right-angled beam deflection in this transitional region of the measuring beam guided to the surface of the measured object and returning from it, whereby the accuracy of the measurement is substantially favored, especially in inaccessible, tight hollow spaces.

An additional improvement, especially in the case of a numerical aperture of the respective optical fiber of 0.12, is achieved by making the angle of inclination at least 48^0.

Furthermore, interferences are suppressed by providing a jacket-like covering of an object-end end section of the probe optical fiber unit with an anti-reflection treatment.

Further possibilities for improving the coupling of the radiation are to provide the exit surface with a reflection treatment.

For the construction and the functioning, one embodiment is advantageous in that a partially transmitting region between a

probe fiber and a fiber section of the measuring probe is formed with the aid of an exit surface of a probe fiber that is slanted at an exit angle with respect to the optical probe axis, and with the aid of an entrance surface of a fiber section following on the object end that is also slanted at an exit angle with respect to the optical probe axis, between the exit surface and the entrance surface a wedge-shaped gap being formed; and the exit surface and the entrance surface being inclined in the same direction with respect to the probe axis.

In this regard, advantageous measures are that the exit angle and the entrance angle are selected so that a Fresnel reflection is effected. The radiation transmission for reliable measuring results is favored by the exit angle α being between 5^0 and 8^0, and the entrance angle being between α and 0^0.

An additional advantageous construction is that the probe fiber and the fiber section are accommodated axially aligned in a tubule-shaped accommodation, which is surrounded by an outer tube of the measuring probe, that on the end face of the accommodation, that faces away from the measured object, a positioning element is provided that surrounds the probe fiber and is also accommodated concentrically to the tube, and that the fiber section is fixed in the object-end, front part of the accommodation and the probe fiber is fixed in the rear part of the accommodation, that is distant from the object, and/or in the tube.

Furthermore, one favorable construction is achieved in that the front part of the accommodation is separated from the rear part of the accommodation by diametrically opposite gaps, the one gap being limited at the rear in the elongation of the slanted exit surface of the probe fiber, and the other gap being limited on the front in the elongation of the slanting

entrance surface, that the front part and the rear part of the receptacle are enclosed by a common sleeve-shaped retaining ring, which is surrounded on the outside by the tube, and that a front section of the fiber section has a lesser diameter compared to its rear section.

Other measures contribute to an advantageous construction and reliable functioning, namely that the modulation interferometer has at least partially a polarization-maintaining, light-conducting structure in the form of an optical fiber conductor or integrated optics, the light-conducting structure being interrupted at at least one arm.

Brief Description of the Drawings

The present invention is elucidated in the following on the basis of exemplary embodiments, with reference to the drawing. The figures show:

Figure 1 a schematic representation of an overall construction of an interferometric measuring device having a modulation interferometer and a measuring probe,

Figure 2 a more detailed embodiment of the modulation interferometer shown in Figure 1,

Figure 3 the measuring probe and the measured object in a side view with a representation of the radiation error in offset,

Figure 4 a schematic representation of a fiber part of the measuring probe in a side view,

Figure 5 the front section of the measuring probe in a schematic lateral representation and

Figure 6 a further exemplary embodiment of the front section of the measuring probe in a schematic lateral representation.

Exemplary Embodiment

As shown in Figure 1, the interferometric measuring device based on the principle of heterodyne interferometry has a broad-band, short-coherent light source 1, whose radiation is supplied to a so-called modulation interferometer 2. In modulation interferometer 2, which is shown in greater detail in Figure 2, radiation s(t) is split up at a first beam splitter 2.3 into a first beam component 2.1 guided via a first arm, having a partial radiation $s_1(t)$ and a second beam component 2.1' guided via a second arm, having a partial radiation $s_2(t)$, and is recombined at the exit side at an additional beam splitter 2.10, and from there it is conducted via a light-conducting fiber device 6 to a distant measuring probe 3. From measuring probe 3, which is constructed, for example, as a Fizeau interferometer or a Mirau interferometer, as is explained in more detail in the documents named at the outset, the radiation subsequently reaches, via an additional light-conducting fiber device 7, a receiver device 4 having a beam splitting unit 4.1 and subsequent photoelectric receivers 4.2, in which a conversion into electrical signals takes place. In a subsequent evaluation unit 5, having a phase detector 5.1 and a computing unit 5.2, the properties of the measuring surface picked up using measuring probe 3 (such as roughness, shape, clearance distance) are then ascertained.

Modulation interferometer 2 is designed as a Mach-Zehnder interferometer, the two arms in connection to first beam splitter 2.3 having first and second entrance-side light-conducting fibers 2.11, 2.11', and first and second exit-side light-conducting fibers 2.12, 2.12', which lead to additional beam splitter 2.10. First beam splitter 2.3 is, in this case, formed in an optical fiber, by which the radiation coming from light source 1 is advanced. At the exit of the coupler thus formed, the beam components are collimated with the aid of

lens-type coupling elements 2.4, 2.4′, and the two collimated beam components pass through a first or a second modulating unit 2.2, 2.2′, for instance, in the form of an acoustooptical modulator, a fiber optic piezo modulator or a thermal phase modulator, the modulating units 2.2, 2.2′ being advantageously able to be developed also as integrated optical components. In order to correct the chromatic dispersion, at least one of beam components 2.1, 2.1′ passes through a glass plate 2.7′ which is situated in a first or a second light path 2.5, 2.5′. The choice of the positioning of the glass plate 2.7′ and/or its thickness is determined by calculation. In their further course, first beam component 2.1 and second beam component 2.1′ are conducted to a first or a second lens-type light guide element 2.6, 2.6′ and coupled into the first or the second exit-side light-conducting fiber 2.12, 2.12′. First or second exit-side light-conducting fiber 2.12, 2.12′ has a greater optical path length than the other light-conducting fiber, to the extent that the optical path difference $\Delta L = L_2 - L_1$ between the two arms is greater than the coherence length of the short-coherent radiation s(t) after running through filters 4.3 and 4.3′. One of the lens-type coupling elements 2.4, 2.4′ or light-conducting elements 2.6, 2.6′, for example, light-conducting element 2.6′, may be fastened to a calibrating device using which the optical path difference ΔL may be adjusted, by hand or with the aid of a motor, for instance, while using a micrometer bench, in such a way that the path difference ΔL between the two arms is tuned to that of measuring probe 3 so as to effect interference using measuring probe 3. Light-conducting fibers 2.11, 2.11′, 2.12, 2.12′ used are monomode. Besides, they are advantageously polarization-receiving, especially if light source 1 is polarized and/or if modulating units 2.2, 2.2′ are formed of double-refractive crystals and/or if installation at the coupling locations does not yield satisfactory stability with

respect to the polarization direction in the two interferometer arms. To achieve the optical path difference, an optical alternate route 2.9' is provided, for example, in second exit-side light-conducting fiber 2.12'.

Probe 3, which is used to detect the object surface, which is designed, for instance, as a Fizeau interferometer or a Mirau interferometer, has a reference branch having a reference plane and a measuring branch leading to the object surface, whose optical path differences are selected so that the path difference generated in modulating interferometer 2 is compensated for, so that the measuring beam coming from the object surface and the reference beam coming from the reference plane interfere when they are superposed. The interfering radiation is supplied to beam splitting unit 4.1 for spectral partitioning into components of different wavelengths, and is subsequently supplied to the allocated photoelectric receivers 4.2. The desired surface property is ascertained from the interfering radiation and the electrical signals obtained from it by evaluating the phase differences, by using phase detector 5.1 and subsequent computing unit 5.2. In this context, the evaluated phase difference is created by the frequency difference, generated by first or second modulating unit 2.2, 2.2', which, corresponding to the heterodyne method is relatively low with respect to the fundamental frequency. The calculation is carried out according to the formula:

$$\Delta\varphi = 2\pi \cdot (2e/\Lambda) + \varphi_0$$

where

φ_0 is a constant,

$\Lambda = \lambda_1 \cdot \lambda_2 / (\lambda_2 - \lambda_1)$ is the synthetic wavelength of the measuring device,

λ_1 is the wavelength at a first photoelectric receiver,
λ_2 is the wavelength at a second photoelectric receiver,
e is the measuring distance.

From this, using evaluation unit 5, the respective recorded clearance distance of the surface at a measuring point is determined from the relationship:

$$e = \Delta\varphi \cdot (2\pi) \cdot (\Lambda/2)$$

Distance measure e is thus determined from a measurement of the phase between two electrical signals, and therefore the measurement is independent of the optical intensity received by the photodiodes.

Figure 3 shows a fiber part of the measuring probe, designed as a Mirau interferometer, having a monomode light-conducting fiber, and the path displacement of the incident $s_2(t)$ and $s_1(t)$, as well as the retracing radiation components $r_1'(t)$, $r_1(t)$, $r_2(t)$ and $r_2'(t)$ from the surface of measuring object 8 and a partially transmitting region 3.3 between an object-side exit surface 3.31 of a probe fiber 3.1 and an entrance surface 3.32, farther away from the object, of a fiber section 3.2. The retracing portions of radiation $r_1'(t)$ and $r_1(t)$ come about, in this context, from that radiation $s_1(t)$ which has passed through the arm of modulating interferometer 2 without alternate route, portion of radiation $r_1'(t)$ being reflected by partially transmitting region 3.3 and portion of radiation $r_1(t)$ being reflected by the surface of measured object 8. By contrast, the retracing portions of radiation $r_2(t)$ and $r_2'(t)$ come about from that radiation $s_2(t)$ of modulating interferometer 2 which has passed through the optical alternate route, retracing portion of radiation $r_2(t)$ having being reflected by partially transmitting region 3.3 and retracing portion of radiation $r_2'(t)$ having being reflected by

the surface of measured object 8. It is shown that, corresponding to the compensation of the path difference ΔL formed in modulating interferometer 2 by measuring probe 3, only the retracing portions of radiation $r_1(t)$ and $r_2(t)$ lie within the coherence length and interfere with each other.

In the exemplary embodiment as in Figure 3, object-side exit surface 3.4 of fiber section 3.2 is inclined preferably at an angle of 45^0 with respect to optical probe axis 3.5. A reflective metallic or dielectric coating is applied to exit surface 3.4. The radiation is bent in this manner essentially at right angles and guided to the surrounding surface of the object, and the radiation reflected by the surface reenters the light-conducting fiber via exit surface 3.4.

As shown in Figures 4 to 6, partially transmitting region 3.3 is formed between exit surface 3.31 of probe fiber 3.1 and entrance surface 3.32 of fiber section 3.2 by an inclination of exit surface 3.31 at an angle α with respect to the normal of probe axis 3.5, and by an inclination of entrance surface 3.32 of fiber section 3.2 at an angle β with respect to the normal of probe axis 3.5, the angle α being greater than the angle β, and a wedge-shaped gap coming about between exit surface 3.31 and entrance surface 3.32. The alignment of the inclination with respect to the normal is oriented in the same manner towards the object in the case of exit surface 3.31 and entrance surface 3.32. Angle α of exit surface 3.31 is selected so that the radiation flow of the Fresnel reflection on exit surface 3.31 is not guided by probe fiber 3.1. For a monomode light-conducting fiber having a numerical aperture of 0.12, the angle α is advantageously about 6^0. Angle β is selected so that the radiation flow of the Fresnel reflection is guided onto entrance surface 3.32 of fiber section 3.2 by probe fiber 3.1, the extent of the radiation

flow that is to be coupled into probe fiber 3.1 being taken into consideration. If angle β is equal to 0^0, the coupling rate amounts to about 3.6 %. If angle β runs counter to angle α, the degree of coupling tends toward 0. If angle β tends counter to angle α, the transmission for this transition and a retracing radiation goes toward 86 %. If, however, angle β is equal to 0^0, the transmission amounts to about 60 %. A numerical aperture of 0.12 comes about, for example, at a wavelength of 1.550 nm and a diameter of 10.4 µm. Angle α should not be selected to be less than about 5^0.

The reflection treatment of exit surface 3.4 of fiber section 3.2 may be reduced or avoided if exit angle γ is increased so as to achieve total reflection at exit surface 7. This is the case, for instance, in the case of a monomode light-conducting fiber having a numerical aperture of 0.12, at an exit angle γ that is above 48^0.

At the object-side end region of fiber section 3.2, an anti-reflection treatment 3.22 may be undertaken on the outer treatment (cladding), in order to reduce the sensitivity with respect to the Fresnel reflection, or exit angle γ may be enlarged to the extent that the radiation flow of this reflection is no longer coupled into fiber section 3.2.

As shown in Figure 5, probe fiber 3.1 and fiber section 3.2 may be accommodated in the same tubule-type accommodation 3.6 and brought into contact. Accommodation 3.6 is the same that is used for connectors of monomode light-conducting fibers. Accommodation 3.6 is inserted into a tube 3.9 of the measuring probe 3 that surrounds it. On the inside of tube 3.9, on the end face of accommodation 3.6 lying away from object, there is subsequently also a positioning piece 3.7 for guiding and preadjusting probe fiber 3.1. Fiber section 3.2 is fixed on the inside of the accommodation with the aid

of adhesives 3.8', while probe fiber 3.1 is fixed in accommodation 3.6 and/or positioning piece 3.7 with the aid of adhesives 3.8.

Another procedure for aligning and fixing probe fiber 3.1 and fiber section 3.2 in probe 3 is shown in Figure 6. Probe fiber 3.1 is introduced into a rear section 3.6' of tubule-type accommodation 3.6, and the front end face of accommodation section 3.6' and of exit surface 3.31 of probe fiber 3.1 are polished at the desired angle, the front end face in the region of the front-most edge of probe fiber 3.1 being aligned normal to optical axis 3.5 of probe fiber 3.1. Accordingly, the rear end face of a front section 3.6" of accommodation 3.6 is polished corresponding to the desired entrance surface 3.32 of fiber section 3.2, the region of the rear end face of front section 3.6" of accommodation 3.6, which is adjacent to the hindmost edge of fiber section 3.2, being aligned normal to optical axis 3.5 of probe fiber 3.1. Between rear section 3.6' and front section 3.6" of accommodation 3.6 there comes about, in this context, the set-up shown in Figure 6 in longitudinal section. The two sections 3.6' and 3.6" of accommodation 3.6 are axially aligned with each other using a retaining ring 3.10 that is applied, for example slotted, and inserted into tube 3.9. Furthermore, in tube 3.9 there is also inserted, in turn, bordering on the rear end face of accommodation 3.6, a concentric positioning piece 3.7 for calibrating and prefixing probe fiber 3.1, as in the exemplary embodiment according to Figure 5. The fixing of probe fiber 3.1 and of fiber section 3.2 using adhesives 3.8, 3.8' thus also takes place corresponding to the exemplary embodiment according to Figure 5, fiber section 3.6 being fixed in front section 3.6" of accommodation 3.6.

It is also possible to align sections 3.6′ and 3.6″ by inserting them into a V-shaped profile. Because the two sections 3.6′, 3.6″ of accommodation 3.6 are inserted separately, the outermost end of measuring probe 3 may be changed immovably and corresponding to the characteristic of the measured object, the same probe fiber 3.1 being retained.

As Figures 4 to 6 also show, the outer section of fiber section 3.2 is reduced in its diameter, so that it may also be introduced into tight holes of a measured object 8, whose diameter amounts to less than 130 μm. The diameter of a monomode light-conducting fiber having outer treatment (cladding) usually amounts to 125 μm. The diameter may be reduced with the aid of chemical treatment using an appropriate acid or of heat treatment, so as to obtain a desired tapering 3.21. Antireflecting treatment 3.22 is then undertaken in the region of the section of lower diameter. These measures, too, contribute to one's being able to undertake reliable measurements even in tight recesses of a measured object 8.